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The Effect of Moisture and Temperature on Optical Coatings Used in Eye-safer Lasers

by Jeffrey O. White, Aaron Z. Chan, and Carl E. Mungan

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14. ABSTRACT
Erbium (Er):yttrium aluminum garnet (YAG) lasers are currently under development at the U.S. Army Research Laboratory (ARL) as eye-safer alternatives to neodymium (Nd):YAG for countering rockets, artillery, and mortar (CRAM). Anomalous increases in laser output have been observed during the 30–60 min period after turn-on. A hypothesis was that one or more of the three optical coatings (anti-reflection, dichroic, and partially reflecting) in the laser cavity were absorbing or desorbing moisture. On the basis of the baking-out measurements described here, we attribute the increase in laser power to moisture being driven out of the dichroic coating, increasing its reflectivity at the laser wavelength. We have also measured the effect of operating temperature on a dichroic coating that has already been baked-out.

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Moisture, optical coatings, lasers

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1. Introduction/Background

Erbium (Er):yttrium aluminum garnet (YAG) Er:YAG lasers are currently under development at the U.S. Army Research Laboratory (ARL) as eye-safer alternatives to neodymium (Nd):YAG for countering rockets, artillery, and mortar (CRAM). Anomalous increases in laser output have been observed during the 30–60 min period after turn-on. A hypothesis was that one or more of the optical coatings in the laser cavity were absorbing or desorbing moisture.

The three basic coatings used in these lasers are (1) high reflecting (HR), (2) anti-reflecting (AR), and (3) partially reflecting (PR) at λ_L = 1645 nm (figure 1). The partial reflector is used as the output coupler (OC). Longitudinal diode pumping at λ_p = 1532 nm implies a low-quantum-defect (7%), but necessitates a dichroic HR coating that has a high transmission at λ_P and a high reflection at λ_L. The HR coating can be either on the rod face or on a separate mirror substrate.

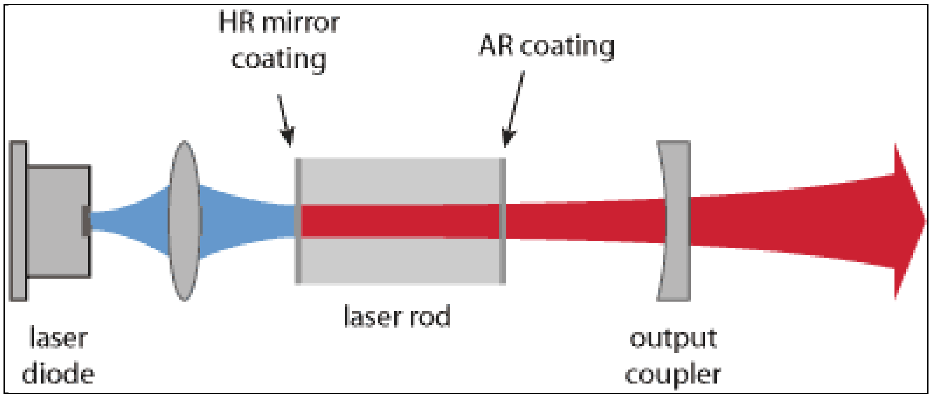

Figure 1. Diode-pumped solid-state rod laser.

All three are lossless dielectric multilayer coatings; therefore, we can assume that the reflection plus the transmission equal one $R + T = 1$ (figure 2). The PR is deposited on BK7 glass with the back side anti-reflection-coated for 1645 nm (*1*). The AR and HR coatings are deposited on witness samples of SF6 glass, which has an index of refraction close to that of YAG (table 1) (*2, 3*). The back sides are polished, but not AR coated, so multiple reflections are present.

Figure 2. (Left to right) Partial reflector, AR coating, and dichroic coating.

Table 1. Index of refraction of the PR substrate, the witness samples, and the laser rod.

	BK7	**SF6**	**YAG**
1532 nm	1.50088	1.76441	1.80725
1645 nm	1.49944	1.76272	1.80565

2. Experiment/Calculations

The three samples were immersed in water overnight to furnish a starting point that could be reproduced easily. It is not known whether the moisture absorbed in this case is greater or less than the amount absorbed over a period of weeks or months at ambient relative humidity (~40%). The experimental sequence was to bake the samples, cool them to room temperature, measure the transmission, and repeat. We assume that the baking process was cumulative, i.e., changes in moisture content occurred only during the baking time, because the cool-down was comparatively rapid, and spectral scanning was done at ~25 °C. The samples were baked in air on a hotplate at a temperature (100 °C) recommended by a vendor, high enough to produce a change in a reasonable time, but far lower than what would damage the coating (*1*). After baking, the samples were cooled for a period of 5–10 min.

The optical transmission was measured at 0° incidence with a spectrophotometer (*4*). Although the only wavelengths of immediate interest are 1532 and 1645 nm, spectra were acquired from 355–1700 nm in case features correlated to water content turned up at other wavelengths (none did). We do not expect multiple reflections from the sample faces to produce interference fringes in the spectra, because the sample faces are not intentionally parallel and the spectrophotometer does not have sufficient resolution.

3. Results and Discussion

The transmission of the AR-coated sample increased by ~1% during 4 h of baking out; after which no further changes were observed (figure 3). The transmission of the sample is less than that of the AR coating alone because of the ~7.6% reflection expected from the air/SF6 interface on the back side. The fine-scale structure in the spectra is due to noise.

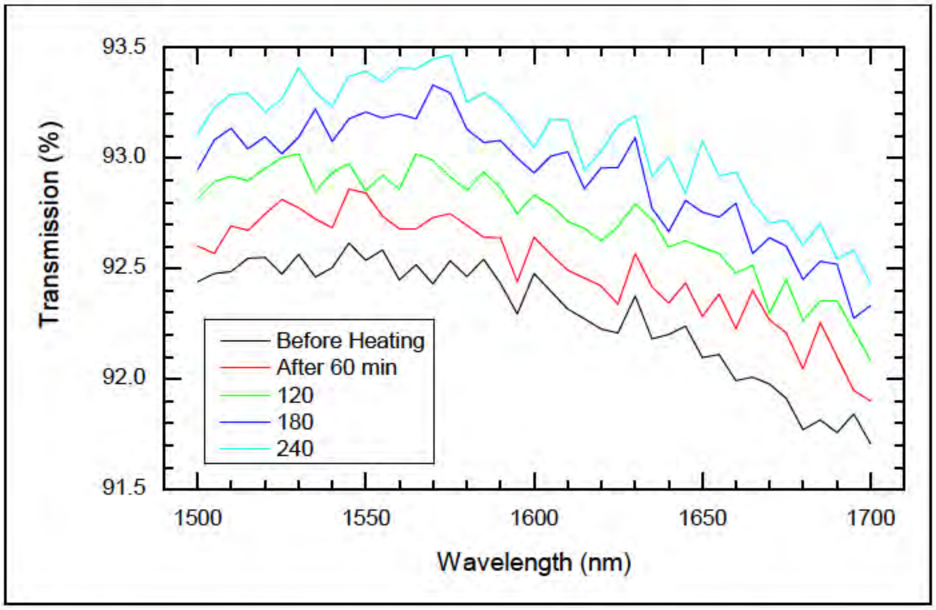

Figure 3. Transmission spectra for AR-coated sample after repeated heating at 100 °C.

On a shorter timescale than that shown in figure 3, the transmission shows an initial drop, which may be spurious (figure 4). The 1532-nm curve in figure 4 is an interpolation between the data taken at 1530 and 1535 nm.

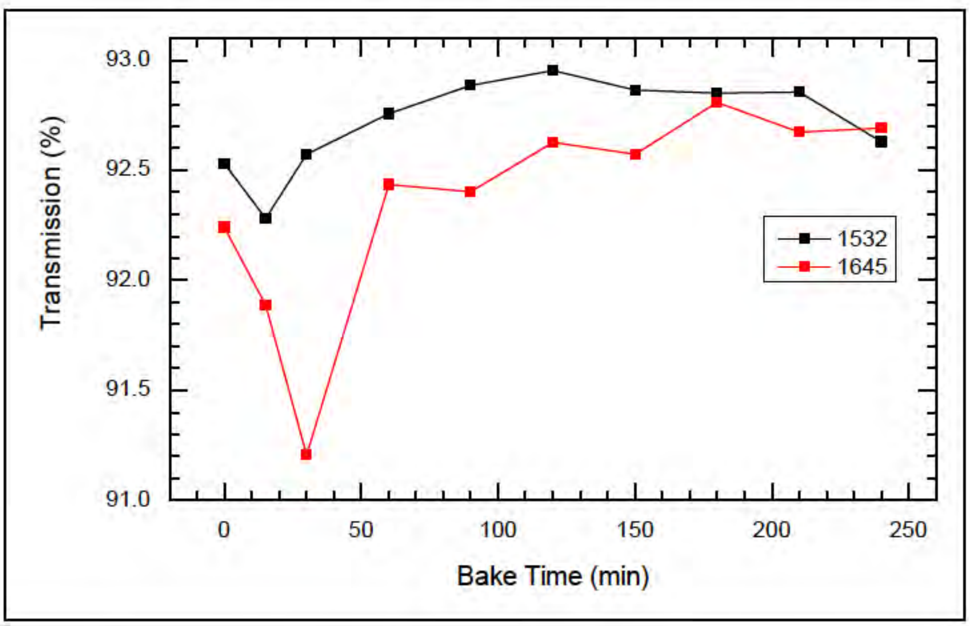

Figure 4. Transmission of AR-coated sample vs. bake time.

The PR sample showed a decrease in T (increase in R) over the course of several hours of baking (figure 5). At 1645, the reflectivity increased from 76.4% to 77.2% (figure 6). The coating run for this substrate was specified to yield a 70% reflector at 1645 nm when ordered. The reflectivity was measured to be 72% by the vendor shortly after deposition, and six months later

measured to be ~80% at ARL. The mirror was returned to the vendor, where baking at 100 °C overnight restored the ~70% reflectivity (*1*)*. Currently, with an identical mirror (except for the substrate radius of curvature), we are seeing an increase in reflectivity during bakeout, for reasons that are unknown.

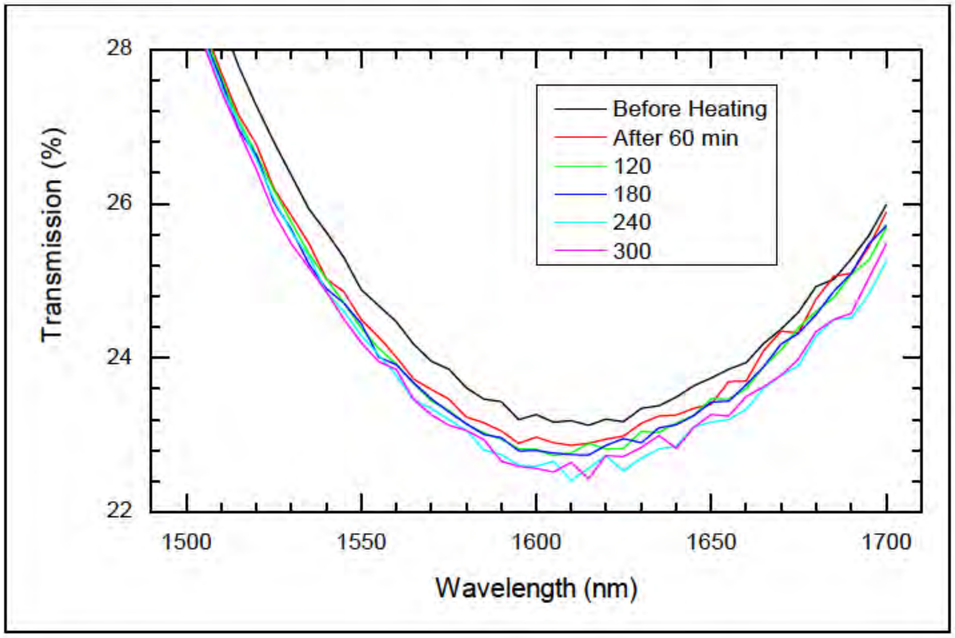

Figure 5. Transmission spectra of PR-coated sample after heating at 100 °C.

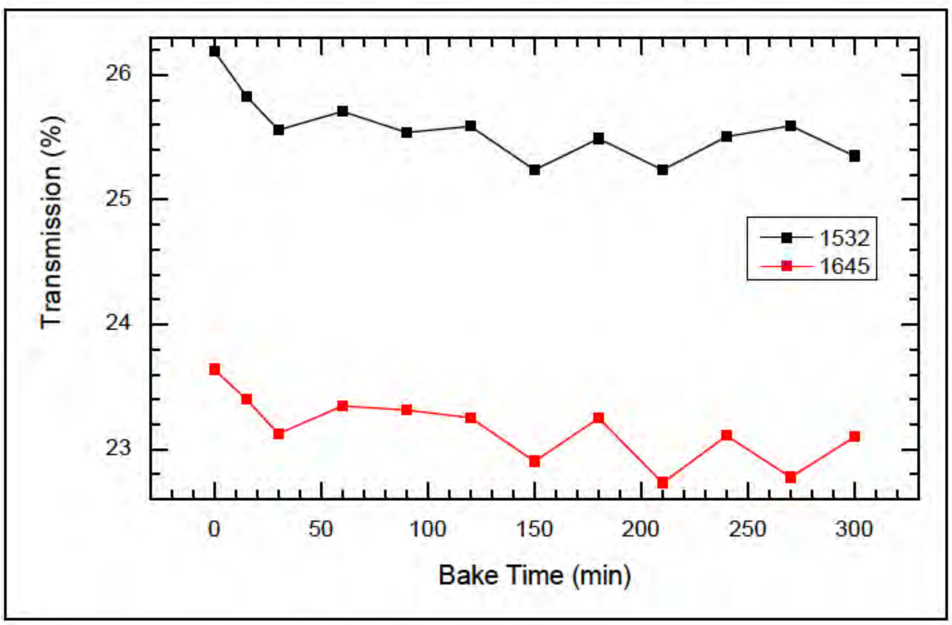

Figure 6. Transmission of PR-coated sample vs. bake time.

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*This observation originally lead us to suspect moisture desorption as the cause for the slow increases in Er:YAG output power after turn-on.

The HR spectrum shifted 32 nm toward the shorter wavelengths during the baking (figure 7). The decrease in transmission at 1532 nm is unfortunate for the Er:YAG laser output power, but the increase in reflectivity (from 95% to >99.5%) at 1645 nm is beneficial (figure 8).

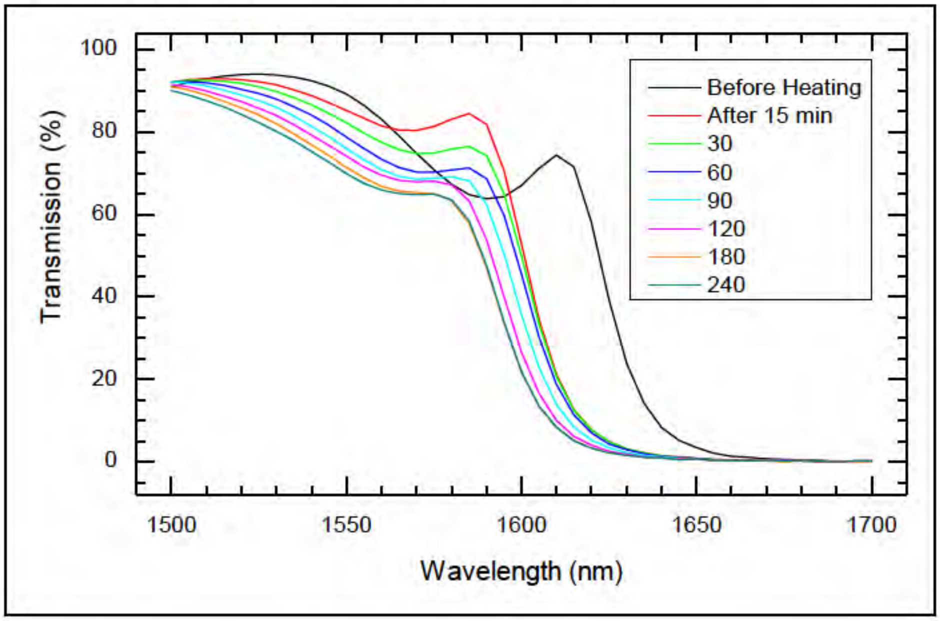

Figure 7. Transmission spectra of HR-coated sample after baking at 100 °C.

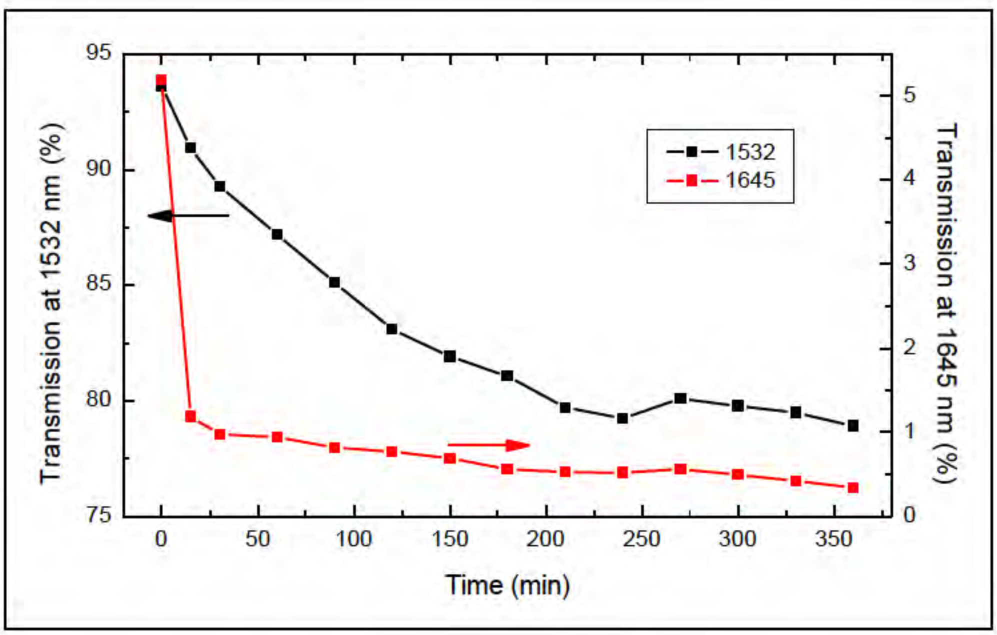

Figure 8. Transmission of HR-coated sample vs. bake time.

We believe that moisture desorption from the HR coating on the Er:YAG rod is the most likely explanation for the gradual increase in laser output power. The effect of moisture on the AR coating was negligible. Although the PR coating was effected by moisture, it not subject to

significant heating during laser operation because the PR is located several centimeters from the rod, and it does not absorb at 1532 or 1645 nm. The Er:YAG rod *does* absorb the pump light at 1532 nm. To reduce heating the HR coating and the O-ring seal to the point of damage, the rod has a 10-mm undoped cap on the end where the pump is incident. The undoped YAG can still conduct some heat from the doped portion out to the coating. Monitoring the temperature of the coating, or the rod, is difficult because the thermal conductivity is low compared to a metal, and a thermocouple placed close enough to the region of interest would shadow the sample, absorb light by itself, etc.

The middle two thirds of the 60-mm rod are cooled with water at 15 °C to dissipate the 30–300 W of heat that is generated when in operation. When not being pumped, the cooling water could induce some condensation on the coated ends of the rod. In view of the care taken to cool the rod, it is ironic that heating turns out to have the beneficial effect of removing moisture from the HR coating. In the future, steps will probably be taken to keep the coatings in a dry atmosphere when not in use.

The effect of moisture on optical coatings has been studied in the past, but not a great deal has been published. The following paragraph is an excerpt from reference 5:

> "In many coatings voids in the microstructure are large enough to allow water which condenses from the atmosphere to enter and spread laterally through the layers (*6–8*). This process may take place over a long period of time and is an important cause of temporal instability of thin-film properties. The most prominent optical effect is a shift of the spectral profile of the coating toward longer wavelengths (*9–12*) due to the increase in effective index of the wet material."

Our observations on the HR coating are consistent with the red shift due to moisture absorption and a blue shift due to moisture removal.

Because the dichroic HR coating may be inadvertently heated during use, despite care taken to keep it cool, we thought it prudent to see how operating temperature affects coating performance. An oven was built and placed inside the spectrophotometer so that transmission spectra could be recorded while a sample is hot (figure 9).

Figure 9. Temperature-controlled oven for use inside the spectrophotometer.

The HR sample was baked for several hours before the measurement began. The results show a ±5-nm movement in the edge, only a slight change in transmission at 1645 nm, and close to zero change at 1532 nm (figure 10).

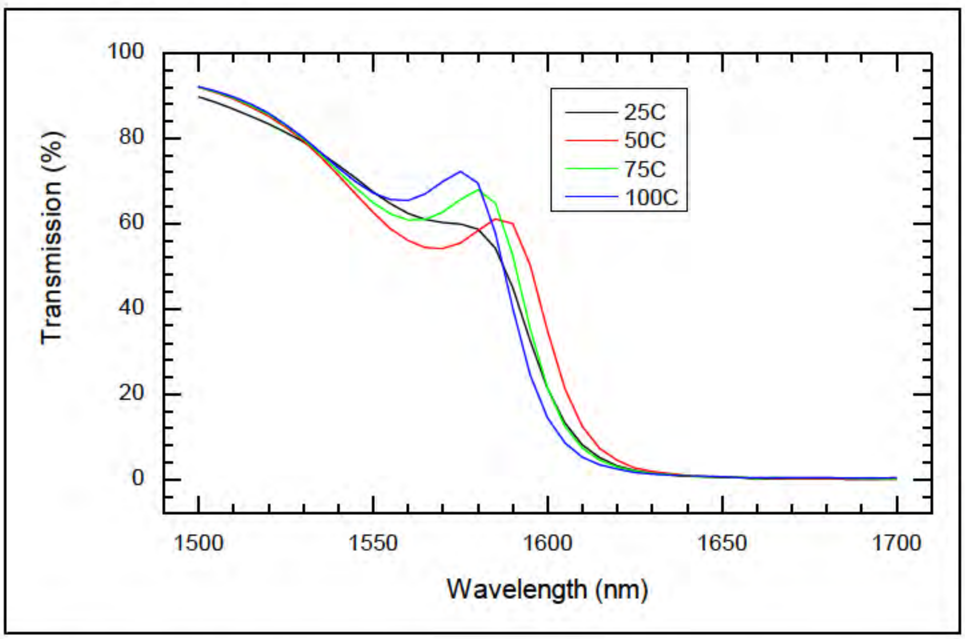

Figure 10. Transmission spectra of HR-coated sample for different temperatures.

4. Conclusions

The results of this study indicate that moisture desorption from the HR dichroic coating on the Er:YAG rod is the most likely explanation for the gradual increase in laser output power. Moisture induces a 30-nm red shift of the transition wavelength in the HR dichroic coating. Coatings by other manufacturers may be less porous and less susceptible to moisture absorption. Another solution would be to keep the laser heads in a dry atmosphere when not in use. Temperatures in the range 25–100 °C had a less-pronounced effect on the transmission spectra.

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List of Symbols, Abbreviations, and Acronyms

AR	anti-reflecting
ARL	U.S. Army Research Laboratory
CRAM	countering rockets, artillery, and mortar
Er	erbium
HR	high reflecting
Nd	neodymium
OC	output coupler
PR	partially reflecting
YAG	yttrium aluminum garnet

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